Decoding Additively Manufactured Functionally Graded Metals Using the Virtual Fields Method

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Abstract. Additive manufacturing (AM) enables the creation of functionally graded metals with tunable local properties for components operating in extreme environments. By gradually varying composition between alloys such as stainless steel 316L and Inconel 625, designers can achieve a balance of strength, ductility, and thermal stability within a single structure. However, capturing the local mechanical behavior within these gradients remains a challenge, as conventional bulk testing obscures the spatial variation inherent to graded systems. This work adopts the “Materials Testing 2.0” framework, leveraging non-traditional coupon geometries and a digital-twin-informed inverse analysis to quantitatively link composition, microstructure, and mechanical response in additively manufactured, functionally-graded SS316L–IN625 alloys. Controlled powder blending and laser-directed energy deposition were used to fabricate gradients with tailored compositional transitions. Quasi-static full-field experiments were conducted to obtain strain maps, which were processed using the Virtual Fields Method (VFM) to extract spatially resolved stiffness and yield properties. The integration of experimental and virtual testing enables efficient decoding of the heterogeneous behavior of graded metallic systems and establishes predictive relationships between composition and performance. In turn, this methodology to characterize additively manufactured functionally graded metals supports data-driven design of next-generation, multifunctional structures.

Introduction

Functionally Graded Materials (FGMs) are an emerging class of materials that can be produced through direct energy deposition additive manufacturing (DED-AM) techniques enabling spatial tailoring of mechanical properties for components operating under extreme conditions. By gradually varying alloy composition, FGMs combine the advantages of multiple materials to improve structural efficiency and thermal or corrosion resistance properties. However, the inherent heterogeneity and spatially varying elastic–plastic response of metal FGMs cannot be characterized using traditional mechanical testing, as conventional methods homogenize the response and fail to resolve local material behavior.

Material Testing 2.0 (MT2.0) is a push to revolutionize conventional testing methods and develop the next generation of experimental methodology that utilizes full-field data to produce rich data sets using inverse identification methods [1,2]. Heterogeneous VFM formulations that have been successfully applied to welded structures [3,6]; however, large material property contrasts lead to poor parameter identifiability using conventional specimen geometries. The novelty of this work lies in integrating heterogeneous VFM with finite element driven specimen topology optimization into a unified framework for elastic–plastic characterization of AM FGMs.

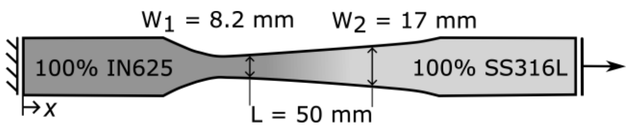

Fig. 1 – Optimized FGM Specimen Geometry

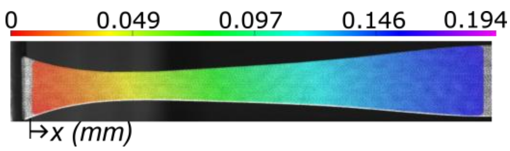

Fig. 2 – Experimental displacement field

Methods

The Material Testing 2.0 framework is used to identify composition-dependent material properties in FGMs by integrating digital-twin finite element validation, topology-optimized specimen design, sensitivity-based virtual fields, and heterogeneous VFM. The specimen is designed to improve the signal-to-noise ratio of the strain fields, informed by sensitivity-based virtual fields, to enhance parameter identifiability [4]. This approach guides the design of specimens that produce strong, well-resolved strain fields across the gauge section, improving the ability to reliably identify material parameters at each composition.

A finite element (FE) model was developed in ABAQUS/Standard 2025 to optimize specimen geometry for elastic-plastic parameter identifiability and to serve as a digital twin for validation of identified properties. An Inconel 625 (IN625)–Stainless Steel 316L (SS316L) FGM with 10% compositional steps was selected due to its relevance in high-temperature aerospace applications and established metallurgical compatibility. The specimen geometry, shown in Fig. 1, was based on a modified ASTM E8/E8M tensile standard with an altered gauge section where the composition varies linearly from 100% IN625 to 100% SS316L.

A MATLAB optimization script was developed to determine a spline-based specimen geometry under an iso-stress assumption, with the objective of maximizing plastic strain across the gauge section and all compositions to enhance plastic parameter identifiability. This geometry is found through the topology optimization function defined in Eq. 1,

$$W_1(x) = \frac{W_2\left[\sigma_{y2}(x)+K_2(x)\left(\varepsilon_{max}-\frac{\sigma_{y2}(x)}{E_2(x)}\right)^{n_2(x)}\right]}{\left[\sigma_{y1}(x)+K_1(x)\left(\varepsilon_{max}-\frac{\sigma_{y1}(x)}{E_1(x)}\right)^{n_1(x)}\right]} \quad (1)$$

where $W_1(x)$ defines the spatial variation of the cross-sectional width, W_2 is the maximum gauge width, ε_{max} is the maximum optimization strain, and $E(x)$, $\sigma_y(x)$, $K(x)$, $n(x)$ denote the spatially varying elastic modulus, yield stress, hardening modulus, and power law exponent, respectively. Preliminary experiments identified Ludwik hardening parameters for SS316L and IN625 to be used in Eq. 1, yielding optimized starting widths of 8.2 mm and 17 mm, respectively. Quasi-static tensile experiments were conducted under displacement control at a strain rate of 10^{-3} using a MTS servo-hydraulic load frame. The specimen surface was prepared with a pseudo-random speckle pattern (average speckle size: 0.3 mm) for digital image correlation (DIC) to analyze the full field deformation shown in Fig. 2.

This heterogeneous VFM formulation uses piecewise virtual fields which splits up the sample into equal regions of interest to individually identify material parameters for each region. This challenge is addressed using a stepped identification strategy in which elastic constants are first identified from linear deformation and subsequently held fixed during plastic parameter identification.

Results and Discussion

Despite the SS316L–IN625 sample being designed with a linear compositional gradient, Fig. 3 and Fig. 4 demonstrates that the resulting elastic modulus and yield strength varies non-linearly because of these material composition changes. The nonlinear behavior observed across the gradient, along with the reduced strength in transition regions with high fractions of stainless steel and Inconel, is primarily driven by compositional effects where key alloying elements are redistributed and secondary brittle laves phases form [5]. This behavior departs from the commonly assumed linear rule of mixtures and indicates that intermediate compositions exhibit a more complex mechanical response emphasizing the necessity of heterogeneous material characterization for AM FGMs. This model material successfully captures spatially varying elastic and plastic properties between two alloys and provides a foundation for extension to more complex alloy mixtures.

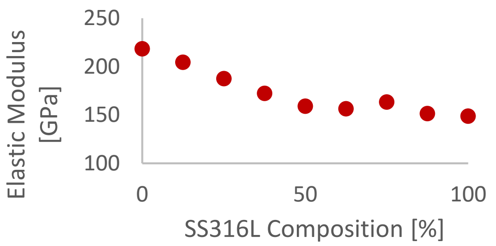

Fig. 3 – Elastic modulus vs SS316L composition

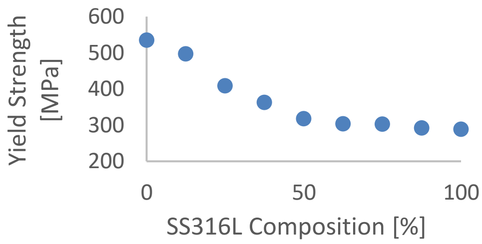

Fig. 4 – Yield strength vs SS316L composition

Conclusion

A Material Testing 2.0 framework combining experimental and computational tools was developed to identify the elastic–plastic behavior of an additively manufactured SS316L–IN625 10% gradient. Using MT2.0, nonlinearities at specific compositions were identified that deviate from expected trends, enabling improved characterization of the influence of compositional variation on elastic–plastic behavior. Utilizing this framework Material 2.0 testing continues to push the bounds of utilizing full field deformations to revolutionize the next generation of mechanical testing for characterizing AM FGMs.

References

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